



Dynamic and thermodynamic processes affecting atmospheric moisture transport to the Arctic during the ARTofMELT expedition in spring 2023

Tuomas Naakka¹, Sonja Murto-Menger², Timo Vihma¹, Michael Tjernström³

5 ¹Finnish meteorological institute, Helsinki, 00560, Finland

²Department of Earth Sciences, Uppsala University, Uppsala, 753 10, Sweden

³Department of Meteorology and Bolin Centre for Climate Research, Stockholm University, Stockholm, 106 91, Sweden

Correspondence to: Tuomas Naakka (tuomas.naakka@fmi.fi)

Abstract. Moisture transport substantially affects the surface energy budget in the Arctic, primarily through its effect on cloud
10 formation. Increased cloudiness enhances downward longwave radiation, which advances the spring onset of snow melt on
top of sea ice. The ARTofMELT expedition, conducted in the Fram Strait in May to early June 2023, aimed to improve
understanding of the processes governing melt onset, which in that spring occurred unexpectedly late. We analysed large- and
synoptic-scale atmospheric circulation patterns affecting moisture transport, being responsible for the dry and cold conditions
15 observed in the Fram Strait. During the first half of the expedition, several cyclones travelled from the Icelandic region towards
Svalbard, but most of the associated moisture transport was directed to the Barents Sea rather than the Fram Strait. This was a
consequence of cyclone tracks being steered by a southwest-northeast oriented jet stream, which was linked to enhanced
baroclinicity, driven by an anomalously warm Norwegian-Barents Sea region and a cold air mass near the North Pole. During
the second half of the expedition, conditions in the Fram Strait were dominated by northerly flow, which sustained dry
20 conditions and temperatures mainly below freezing point, except of the last four days. On these days, the large-scale circulation
resembled that of the first half of the expedition, however, the flow had a stronger meridional component, and baroclinicity
near the Fram Strait was weaker. Our result indicated that adiabatic lifting along frontal zones was the primary mechanism for
water vapour removal, particularly under baroclinic conditions.

1 Introduction

Atmospheric moisture transport to the Arctic is a fundamental component of the Arctic water and energy cycles (Groves and
25 Francis, 2002; Vihma et al., 2016). In the circumpolar Arctic, approximately 55 - 60% of the total atmospheric moisture input
originates from lateral transport from lower latitudes, while the remaining 40 - 45% is supplied by local surface evaporation
(Dufour et al., 2016). This balance exhibits pronounced seasonal variability, with the strongest poleward moisture transport
occurring in summer and early autumn, when the atmospheric moisture-holding capacity is highest (Dufour et al., 2016;
Naakka et al., 2019).



- 30 Poleward moisture transport involves latent heat fluxes, as water vapour carries substantial energy that is released during condensation in the Arctic atmosphere. This latent heat release contributes to warming of the lower troposphere and modifies atmospheric stability. Consequently, both near-surface air temperature and cloud properties (including cloud fraction, vertical structure, condensate content, and phase) are affected (Liu et al., 2019). Changes in clouds, in turn, strongly influence the surface radiation balance (Singh et al., 2025) and precipitation processes, making both the amount and phase (rain versus
- 35 snow) of Arctic precipitation highly sensitive to variations in moisture transport (Hao et al., 2021). Clouds play a particularly important role in enhancing downward longwave radiation, which is the component of the surface energy budget that most strongly controls the timing of spring snowmelt onset on Arctic sea ice (Maksimovich and Vihma, 2012; Murto et al., 2026). The onset of surface melt in spring or early summer is a key stage in the seasonal evolution of sea ice, as it initiates a decrease in surface albedo and thereby increases the absorption of solar radiation (Kapsch et al., 2013;
- 40 Stroeve et al., 2014), which in turn delays the autumn freeze-up (Laxon et al., 2003). Advection of warm and moist air masses into the Arctic has been shown to advance melt onset over the Arctic Ocean (Kapsch et al., 2013; Mortin et al., 2016; Kapsch et al., 2019). Once melt has begun, the reduced surface albedo, together with increasing solar insolation, promotes continued melting even under conditions where turbulent heat fluxes and longwave radiative fluxes alone would not favour melt (Wang et al., 2015). Nevertheless, downward longwave radiation and turbulent heat fluxes remain
- 45 critical for initiating melt, and their enhancement is often associated with intrusions of warm, moist air into the Arctic (Kapsch et al., 2013, Mortin et al., 2016, Kapsch et al., 2019). Heat and moisture transport into the Arctic is governed by large-scale and synoptic-scale atmospheric circulation patterns. Circulation patterns with strong meridional flow component, which is often associated with high-pressure blocking, steer cyclones towards the inner Arctic and thus favour substantial heat and moisture transports into the Arctic (Woods et al., 2013,
- 50 Luo et al., 2017, Fearon et al., 2021, Murto et al., 2022, Svensson et al., 2023). Strong moisture transport events are typically associated with atmospheric rivers, which are narrow bands of enhance water vapour transport from the midlatitudes to high latitudes and are often located in the warm sector of synoptic cyclones (Neiman et al., 2008). Atmospheric rivers account for a substantial fraction of the total poleward moisture transport (Newman et al., 2012, Nash et al., 2018) and can significantly affect the surface energy balance over sea ice (Murto et al., 2023, Zhang et al., 2025).
- 55 Longwave radiative cooling and interactions with a cold surface drive air mass transformation, causing drying and cooling of northward-transported air (Curry 1983, Pithan et al., 2018, Ali and Pithan 2020, Svensson et al., 2023, Karalis et al., 2025). However, drying is not solely governed by thermodynamic processes; dynamic processes also play an important role (Wendish et al., 2025), particularly since barotropic conditions that favour clear air mass transformation are relatively rare (You et al., 2022a).
- 60 Large-scale circulation patterns influence the evolution and tracks of cyclones, thereby substantially affecting their ability to transport moisture into the Arctic (Faeron et al., 2021; Sinclair and Dacre 2019). Faeron et al., (2021) showed that cyclones following strongly meridional tracks transport moisture poleward more efficiently than cyclones with almost zonal tracks. This finding is in line with previous studies showing that blockings often favour strong poleward moisture transport (Woods et al.,



2003). Based on these findings, we hypothesize that the strong baroclinicity associated with a strong zonal jet stream suppresses moisture transport into the Arctic compared with more barotropic conditions. Under strongly baroclinic conditions, cyclones tend to propagate mostly eastward, and their warm sectors, where moist air is transported northward, typically occlude before the cyclone undergoes substantial northward displacement. In these conditions, a large part of the moisture is removed through condensation in the frontal zones bounding the warm sector of cyclone, where uplift and adiabatic cooling of warm and moist air occur. In contrast, barotropic or weakly baroclinic conditions are often associated with atmospheric blocking, weaker zonal flow and stronger meridional flow. Under such conditions, cyclone tracks are more meridional, and cyclones experience a greater poleward displacement during their lifetime. This enables the warm sector and its moist air mass to penetrate farther north before substantial moisture loss occurs in frontal ascent zones. The longer poleward transport pathway also allows more time for thermodynamic processes to modify the air mass properties, which can lead to substantial air mass transformation before it reaches the Arctic.

Although the importance of variability of large-scale circulation and cyclones for moisture transport into the Arctic, as well as the roles of dynamic and thermodynamic process in drying northward-transported air masses are well recognized, significant knowledge gaps remain regarding the underlying mechanisms, their interactions, and their impacts. In particular, improved quantitative understanding is needed of frontal processes associated with cyclones and of the factors controlling air mass drying along transport pathways toward the central Arctic. Our study contributes to filling these gaps by examining how variation in large-scale circulation affect cyclone tracks and evolution, and how these changes subsequently affect dynamical and thermodynamical processes linked to cyclone frontal structures that govern poleward moisture transport. These interactions affecting moisture transport during the ARTofMELT (Atmospheric Rivers and the onset of sea-ice melt; Tjernström and Zieger et al., 2025) expedition are investigated in this study. The ARTofMELT expedition was conducted in the Fram Strait in spring 2023, with the aim of observing the onset of sea-ice melt (Tjernström and Zieger et al., 2025). The spring season in the Fram Strait was relatively cold and dry, and the onset of surface melt occurred unusually late, in almost mid-June. This study examines the factors contributing to these cold, dry conditions by (1) diagnosing the large-scale circulation patterns during the expedition and their influence on moisture transport into the Fram Strait, and (2) quantifying the relative contributions of dynamical and thermodynamical processes to evolution of air mass moisture content both locally over the Fram Strait and along transport trajectories leading into the region.

2 Data and methods

The study is based on synoptical analysis of circulation patterns and analysis of evolution of air masses based on backward trajectories. The data used for both synoptical analysis and calculation of trajectories was taken from ERA5 reanalysis. In addition, ERA5 reanalysis was compared with radiosonde observations collected from soundings launched aboard the Swedish icebreaker *Oden* during the ARTofMELT-expedition.



95 2.1 ERA5 reanalysis

ERA5 reanalysis (Hersbach et al., 2020; Hersbach et al., 2023a; Hersbach et al., 2023b) is the latest reanalysis version from the European Centre for Medium-Range Weather Forecast (ECMWF). It has been shown that ERA5 is best performing global reanalysis in the Arctic (Graham et al., 2019) and able to accurately present the synoptic scale flow structures, even though there are known biases especially in temperature in Arctic boundary layer in ERA5. Batrak and Müller (2019) and Wang et al., (2019) have shown that ERA5 has warm bias near the surface. Tjernström et al., (2021) found that this warm bias extends through the boundary-layer also in forecasts with the ECMWF Integrated Forecasting System, the atmospheric forecast model used in ERA5 but also found a substantial lower troposphere cold bias aloft. For evaluating biases in the period of this study we compared ERA5 with sounding observation taken during the ARTofMELT expedition. However, this comparison is not able to represent ERA5 performance generally in the Arctic as the soundings were assimilated into ERA5 reanalysis and thus they have strongly impacted meteorological fields nearby the sounding location. Therefore, biases in ERA5 are smaller nearby sounding station when soundings were assimilated compared with situations when sounding observation are not available. Even though assimilation improve representation of meteorological condition their effect on model performance of presenting physical and dynamical processes is probably minimal. Hence, this study benefits from the assimilated soundings as they probably improve the presentation of atmospheric condition in our study area. Overall, we assume ERA5 is able to accurately enough present physical and dynamical processes affecting the changes of atmospheric moisture in the Arctic. Surface cyclones and anticyclones are identified using the MOAAP tracking algorithm (Prein et al., 2023). Six-hourly ERA5 sea-level pressure (SLP) fields are remapped to a 25-km equal-area grid to enable cyclone tracking over the pole, and the MOAAP algorithm is then applied. Cyclones are defined as continuous regions in the SLP anomaly field with at least -8 hPa and persisting at least for 12 hours. Their significance is assessed relative to a 40-year climatology (1981-2020).

115 2.2 ARTofMELT soundings

During the ARTofMELT expedition radiosondes were launched 4 times per day (00 UTC, 06 UTC, 12 UTC, 18 UTC) between 9 May 12 UTC and 13 June 12 UTC and 8 times per day (3-hour intervals) between 10 June 15 UTC and 12 June 21 UTC using Vaisala RS41 Radiosondes (Murto et al., 2024a). This sonde type has demonstrated ability to accurately measure atmospheric moisture also in cold conditions when absolute humidity is low and can reliably measure atmospheric humidity even under cloudy conditions (Jensen et al., 2016). However, because the sondes were launched from the helicopter deck of *Oden*, measurements in the lowest ~ 100 m may have been affected by the presence of *Oden*. In particular, when a sonde passed through *Oden*'s exhaust plume, the observations exhibited a warm bias. This warm bias occurred approximately 20% of sounding profiles. The warm bias was corrected in the data set used in the study (Murto et al., 2024a) but was included in the raw sounding profiles which were assimilated in ERA5.



125 2.3 LAGRANTO trajectories

Evolution of air mass properties origin and routes to the Fram Strait were examined based on air mass backward trajectories calculated by the Lagrangian Analysis Tool (LAGRANTO; Sprenger and Wernli 2015, Murto et al., 2024b). LAGRANTO has been developed at the Eidgenössische Technische Hochschule Zürich (ETH Zürich) and utilized in this study for calculation of backward trajectories from the locations of *Oden*. The backward trajectories were calculated hourly starting from 14 different levels in the troposphere ranging from 10hPa above ground level up to 300 hPa levels. Variables along the trajectories were stored 1-hour intervals. The four last days (96h) of the backward trajectories were utilized in the study. The trajectory calculations were based on ERA5 reanalysis. Temperature, potential temperature, specific humidity and pressure as well as horizontal location were traced along the trajectories.

2.3.1 Adiabatic and Diabatic contributions on moisture condensation

Both adiabatic and diabatic processes affect temperature changes of air parcels. In the Arctic adiabatic cooling, i.e., due to upward motion of air, is mostly associated with large-scale dynamics and to some extent to localized convection over open ocean surface in cold seasons. Thus, large-scale dynamics are largely responsible for decreases of temperature in an air parcel. However, diabatic processes, i.e. latent heat release, and divergence of radiative and turbulent heat fluxes also change the temperature of the air parcel. Following Wendish et al., (2025), based on evolution of atmospheric pressure, air temperature, potential temperature and specific humidity along the trajectories, we calculated the contribution of adiabatic and diabatic processes on moisture condensation. The total temperature tendency (DT/Dt , Eq. 1) of the air parcel is divided into the tendency due to adiabatic process (1st term on right hand side) and the tendency due to diabatic process (2nd term on right hand side) utilizing the thermodynamic equation,

$$145 \quad \frac{DT}{Dt} = \left(\frac{DT}{Dt}\right)_{adiabatic} + \left(\frac{DT}{Dt}\right)_{diabatic} = \frac{R}{c_p} \frac{T}{p} \frac{Dp}{Dt} + \left(\frac{p}{p_0}\right)^{\frac{R}{c_p}} \frac{D\theta}{Dt} \quad (1)$$

where adiabatic temperature changes are related to changes in air parcel pressure (Dp/Dt) whereas diabatic temperature changes are associated with changes in potential temperature ($D\theta/Dt$). In Eq. (1) R is gas constant of dry air, c_p is specific heat of air in constant pressure, p is pressure p_0 is pressure in reference level i.e. 1000 hPa.

150 We further divide the diabatic temperature tendency into contributions of latent heat release (1st term in right hand side in Eq. 2) and all other processes, $(DT/dt)_{rad_and_turb}$, which are mainly the convergences of radiative and turbulent heat fluxes.

$$\left(\frac{p}{p_0}\right)^{\frac{R}{c_p}} \frac{D\theta}{Dt} = \frac{L}{c_p} \frac{Dq}{Dt} + \left(\frac{DT}{Dt}\right)_{rad_and_turb} \quad (2)$$

In Eq. (2), L is the latent heat of water vapour condensation and q is specific humidity.



155 Saturation pressure of water vapour is related to temperature through the Clausius-Clapeyron relationship and thus decrease
 in temperature causes moisture condensation if the air parcel is saturated. Changes in temperature, and thus in saturation
 pressure of water vapour, in the air parcel are associated with adiabatic heating/cooling due to vertical motions (1st term on
 right hand side in Eq. 1) or thermodynamic processes such as latent heating (1st term on the right-hand side in Eq. 2), or other
 physical processes (2nd terms on the right-hand side in Eq. 2). The contributions of adiabatic and diabatic processes to moisture
 160 condensation were evaluated by calculating temperature changes in the air parcel resulting from pressure decrease due to uplift
 (adiabatic effects) and from the divergence of radiative and turbulent heat fluxes (diabatic effects) during time steps when
 specific humidity decreased. We assume that the adiabatic and diabatic contributions to condensation are related to the ratio
 of temperature changes caused by these processes. Utilizing this assumption, we can calculate contributions of adiabatic,
 (Dq/dt)_{adiabatic}, and diabatic processes, (Dq/dt)_{rad_and_turb}, on water vapour condensation based on equations (3-4)

$$165 \quad \left(\frac{Dq}{Dt}\right)_{adiabatic} = \begin{cases} \max \left\{ \frac{Dq}{Dt}, -\frac{Dq}{Dt} \frac{\left(\frac{DT}{Dt}\right)_{adiabatic}}{\left|\left(\frac{DT}{Dt}\right)_{adiabatic} + \left(\frac{DT}{Dt}\right)_{rad_and_turb}\right|} \right\}, & \text{when } \frac{Dq}{Dt} < 0 \text{ and } \left(\frac{DT}{Dt}\right)_{adiabatic} < 0 \\ 0, & \text{when } \frac{Dq}{Dt} > 0 \text{ or } \left(\frac{DT}{Dt}\right)_{adiabatic} > 0 \end{cases} \quad (3)$$

$$170 \quad \left(\frac{Dq}{Dt}\right)_{rad_and_turb} = \begin{cases} \max \left\{ \frac{Dq}{Dt}, -\frac{Dq}{Dt} \frac{\left(\frac{DT}{Dt}\right)_{rad_and_turb}}{\left|\left(\frac{DT}{Dt}\right)_{adiabatic} + \left(\frac{DT}{Dt}\right)_{rad_and_turb}\right|} \right\}, & \text{when } \frac{Dq}{Dt} < 0 \text{ and } \left(\frac{DT}{Dt}\right)_{rad_and_turb} < 0 \\ 0, & \text{when } \frac{Dq}{Dt} > 0 \text{ or } \left(\frac{DT}{Dt}\right)_{rad_and_turb} > 0 \end{cases} \quad (4)$$

3 Results

3.1 Large-scale circulation during ARTofMELT and its effect on heat and moisture anomalies

175 Based on a subjective inspection of the large-scale circulation patterns, we divided the whole expedition period from 8 May
 to 13 June into three sub-periods (Table 1). During the first sub-period, large-scale atmospheric circulation over the northern
 North Atlantic was characterised by southwest – northeast directed upper-tropospheric flow (Fig. 1a). On average, the lowest
 geopotential heights at the 300-hPa level were located near the North Pole, with upper-tropospheric troughs extending from



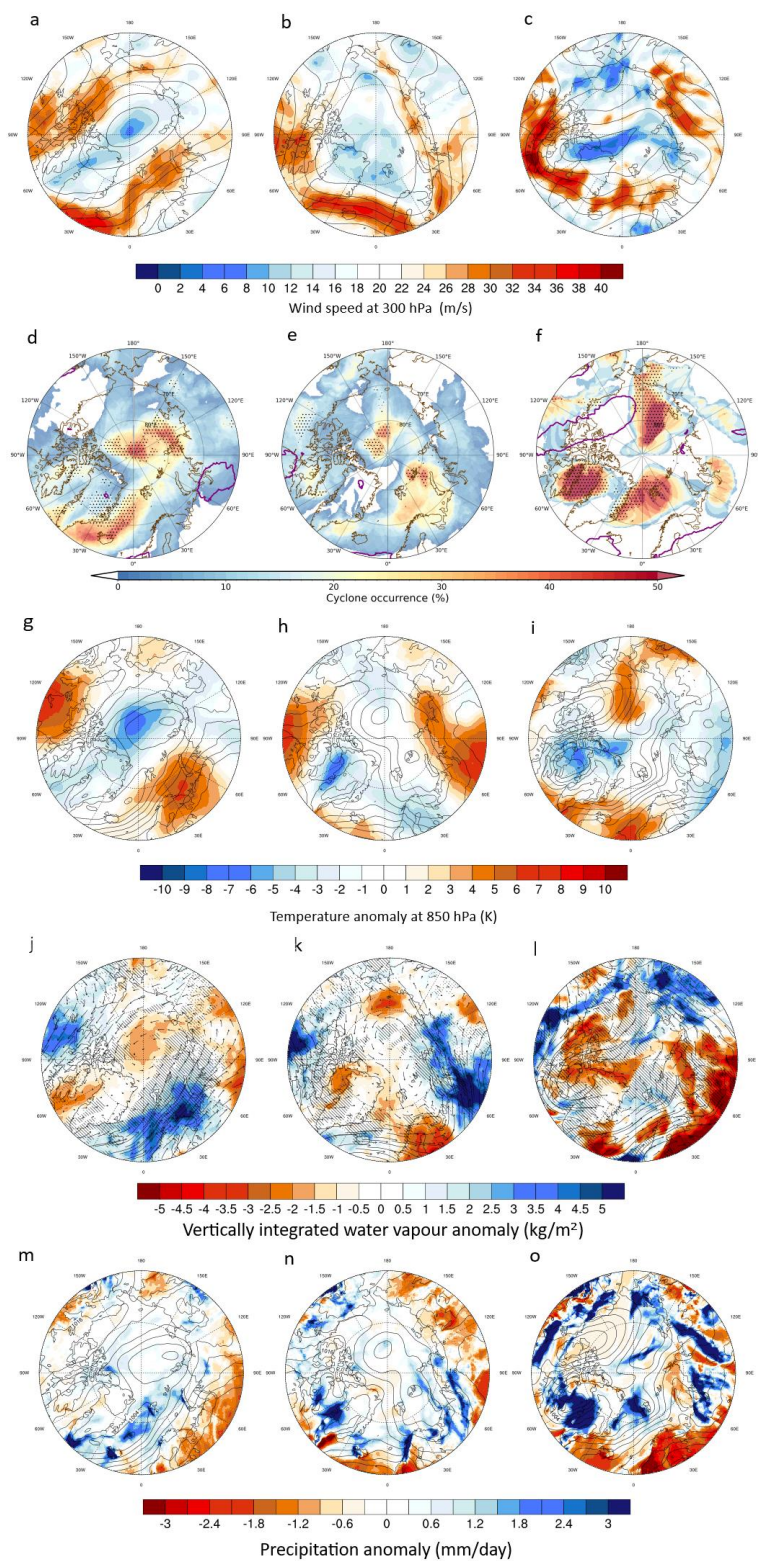
the pole towards Greenland's western side and Siberia. This geopotential pattern allowed formation of a jet stream directed from south-west to north-east over the northern North Atlantic. The average location of the jet stream was from the southern side of Greenland to the Barents Sea. The jet stream was, however, not stationary; its location and strength fluctuated during the sub-period.

Table 1. Periods.

Period	Time range	Length	Description
1	8 May – 25 May	18 days	Eastward moving cyclones
2	26 May – 9 June	15 days	Northerly flow in the Fram Strait
3	10 June – 13 June	4 days	Warm and moist advection to the Fram Strait

During the first sub-period, transient cyclones occurred most frequently in the area from the Denmark Strait to the Svalbard (Fig. 1d) which is also the area of the lowest average mean sea level pressure in the first period (Fig. 1g). The highest cyclone occurrence was near Iceland, and the occurrence gradually decreased towards Svalbard (Fig. 1d). Another maximum of cyclone occurrence was located near the North Pole associated with a local minimum of mean sea-level pressure. However, cyclones only rarely moved from Greenland Sea towards Greenland, as indicated by a large gradient in cyclone occurrences between the eastern and western sides of the Fram strait. The cyclones mainly moved from south-west to north-east carrying warm, moist air from the northern North Atlantic towards the Barents Sea. The warm-air advection contributed to the formation of a warm anomaly over the Barent Sea, where the air mass was on average ~5 K warmer than the 30-year climatological mean (Fig. 1g). The air mass near the pole was colder than average, and the temperature anomalies enhanced baroclinicity in the region between Iceland and Franz Josef Land, thereby contributing to cyclone development.

North-eastward moving cyclones also contributed to moisture transport from the northern North Atlantic towards the Barents Sea (Fig. 1j). The largest positive moisture anomalies occurred over the Norwegian and Barents Seas, where the vertically integrated atmospheric water vapour content was 3 – 5 kg m⁻² higher than the 30-year climatological mean. The largest moisture transport convergence occurred on the northern and eastern sides of the largest atmospheric moisture content anomaly. In this region (marked by hatching in Fig. 1j), the moisture transport convergence exceeded 1 kg m⁻² day⁻¹, indicating notable precipitation in the area. In fact, there was positive anomaly in precipitation in Iceland, Greenland, and Barents Sea region (Fig. 1m).





205 **Figure 1. Summary of large-scale parameters (columns) for the three periods (rows). Shown are (a-c) the average geopotential height (contours, in Pa) and mean wind speed (colours, in m s⁻¹) at 300 hPa level, (d-f) occurrence of cyclones (colours, in % with stippling indicating statistically significant deviation at 90%), with purple line indicating 40% occurrence of anticyclones, (g-i) average mean sea-level pressure (hPa) and temperature anomaly at 850 hPa (K), (j-l) vertically integrated average moisture transport (vectors), anomaly of vertically integrated atmospheric water vapor content (colours, kg m⁻³), and convergence of moisture transport exceeding 1.0 kg day⁻¹ (stippling), and (m – o) average mean sea-level pressure (hPa) and precipitation anomaly (mm). The three different periods are shown in the columns, with (a,d, j, g, m) Period 1(8 – 25 May), (b, e, h, k, n) Period 2 (26 May – 9 June), and (c, f, l, i, o) Period 3 (10 – 13 June)**

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During the second sub-period, an upper tropospheric trough formed around Svalbard while the trough over Greenland became weaker (Fig. 1b). This changed the jet stream so that it extended from the northern side of Iceland towards Scandinavia, and thus transient cyclones took routes far south of the Fram Strait – Svalbard region (Fig. 1e). However, on 30 and 31 May the upper tropospheric flow pattern was remarkably wavy, and the jet stream was orientated from Novaya Zemlya towards Svalbard (Fig. S1). Transient cyclones were mostly located on the eastern side of the upper tropospheric trough in the Barents Sea and around Franz Josef Land (Fig. 1e). This is seen as, on average, the lowest mean sea-level pressure in the area (Fig. 1h). In the beginning of the sub-period, there was also a strong cyclone in the northern North Atlantic, but its route was far south from the Fram Strait (Fig. S2 and S3). After this an anticyclone developed in the northern North Atlantic. Low pressure on the eastern side of Svalbard caused northerly flow in the Fram Strait, bringing dry, cold air from the central Arctic, contributing to formation of a cold and dry anomaly in the area from the Fram Strait to Scandinavia (Fig. 1h and 1k). Precipitation was lower than average around the Fram Strait. Instead, over open ocean in Greenland and Norwegian sea, precipitation was stronger than average, suggesting formation of convective precipitation in the cold air mass (Fig. 1n).

225 During the third sub-period, the upper-tropospheric trough moved eastwards. Simultaneously, a weak blocking, formed in the northern North Atlantic at the end of the second period, also moved eastwards, steering a cyclone along the western flank of the high-pressure system over northeastern Europe towards the Fram Strait. Compared with the first sub-period, the cyclone track was slightly farther north, probably due to the influence of the anticyclone over northeastern Europe (Fig. 1f). As the cyclone approached the Fram Strait, it advected heat and moisture into the region. The advection of a warm, moist air mass led to the formation of positive temperature and moisture anomalies at the 850-hPa level northeast of Svalbard (Fig. 1i and 1l), along with a remarkable increase in moisture convergence and precipitation over the eastern and northern parts of the region (Fig. 1l and 1o).

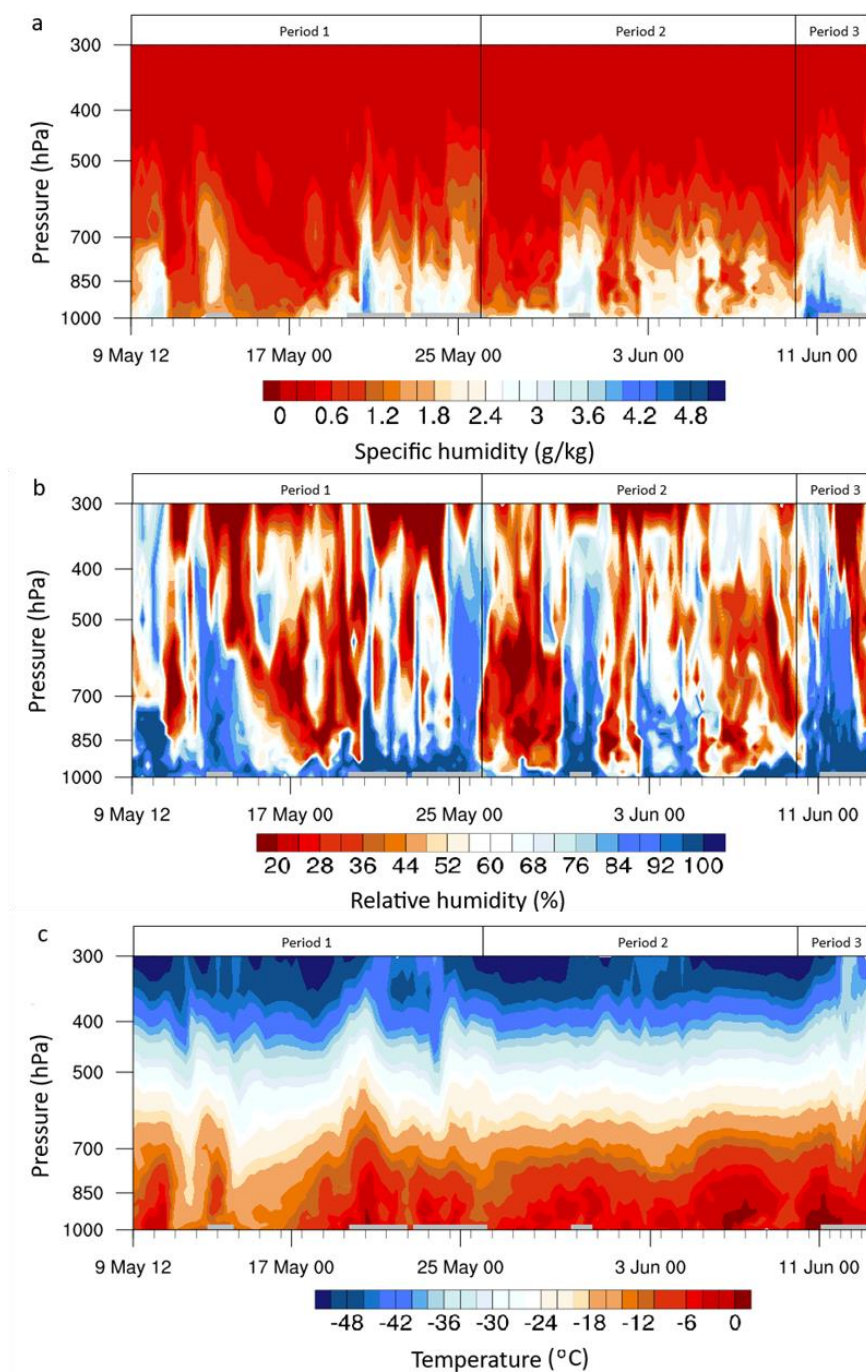
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3.2 Moisture conditions in the Fram Strait and comparison of ERA5 with sounding observations

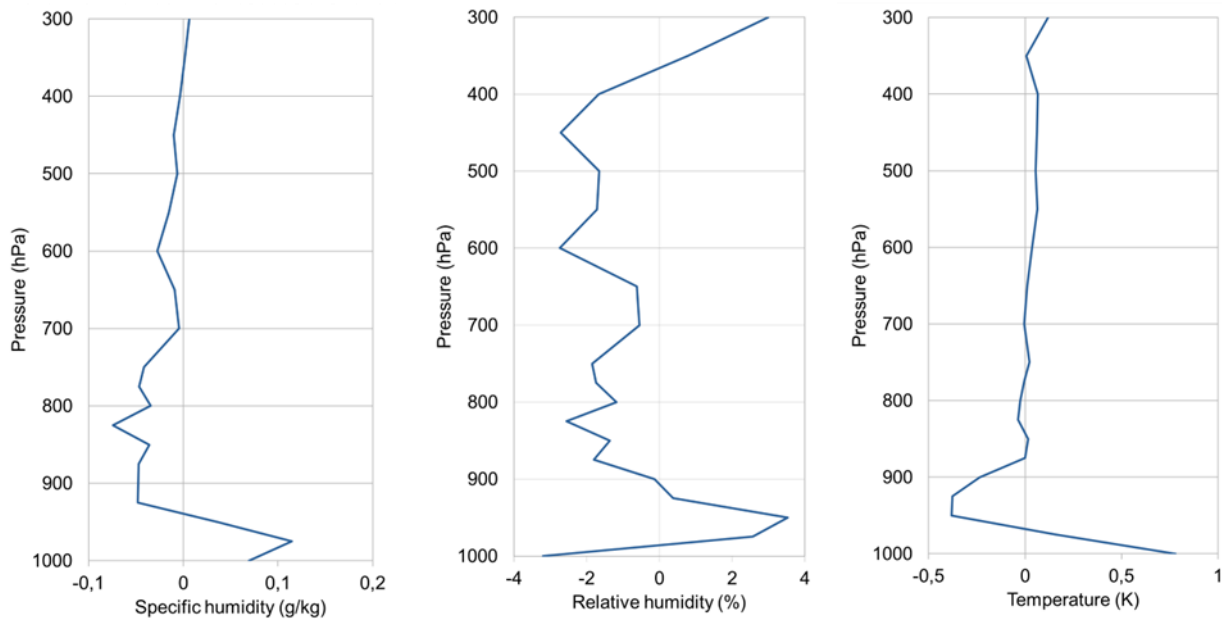
Figure (2) shows the evolution of air temperature, specific and relative humidity during the ARTofMELT expedition based on radiosonde soundings launched from *Oden*. Comparison of radiosonde soundings and ERA5 reanalysis showed that on average, ERA5 agrees well with the observations (Fig. 3). On average, ERA5 has only a small bias in specific humidity, mostly less than 0.1 g kg⁻¹ (Fig. 3a). The bias in specific humidity was largely caused by relative humidity differences between ERA5



240 and radiosonde observations, whereas temperature differences between sounding observations and ERA5 were very small above 875 hPa level, and thus they cannot substantially contribute to specific humidity differences between ERA5 and soundings. Overall, tropospheric temperatures above 900 hPa were nearly identical in ERA5 and radiosonde observations. Thus, ERA5 accurately reproduced the temperature and humidity profiles near the *Oden* during ARTofMELT, likely aided by the assimilation of radiosonde observations.



245 **Figure 2.** Specific humidity (a), relative humidity (b) and temperature (c) profiles from radiosonde soundings launched from IB Oden during ARTofMELT expedition. Grey bars at 1000 hPa level indicate surface pressure lower than 1000 hPa and thus there is not data at 1000 hPa level.



250 **Figure 3. Mean bias of specific humidity (a), relative humidity (b) and temperature (c) in ERA5 in comparison with soundings launched from *Oden* during the ARTofMELT expedition.**

Moist air masses with specific humidity exceeding 4 g kg^{-1} very rarely (only on 20 May and 10-12 June) occurred at *Oden* during the ARTofMELT expedition (Fig. 2a). However, several moist pulses were observed when specific humidity did not exceed 4 g kg^{-1} but exceeded the 30-year climatological mean: 1) 10 May, 2) 13 May, 3) several times between 19 – 25 May, and 4) 29 – 31 May (Fig. S5). These pulses of moist air were associated with advection of warm air, and during these cases also the near-surface air temperatures were above the 30-year climatological mean (Fig. S2 and S5), and relative humidity values were high, mostly above 95% (Fig. 2b).

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	8 May	9 May	10 May	11 May	12 May	13 May	14 May	15 May	16 May	17 May	18 May	19 May	20 May	21 May	22 May	23 May	24 May	25 May	26 May	27 May	28 May	29 May	30 May	31 May	1 June	2 June	3 June	4 June	5 June	6 June	7 June	8 June	9 June	10 June	11 June	12 June	13 June		
300 hPa	0	0	0	0	0	0	0	0	0	0	0	0	3	5	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	1	1	0	13	
400 hPa	0	1	2	0	7	3	0	5	3	0	2	8	4	5	4	3	11	10	6	0	3	10	4	1	0	0	1	0	0	0	0	0	0	0	1	1	6	1	9
500 hPa	0	0	2	1	11	5	0	11	1	1	0	2	17	7	4	3	14	15	6	0	0	9	15	1	1	1	3	0	1	0	0	0	0	1	2	6	14		
600 hPa	0	0	8	1	8	9	8	1	0	3	7	0	11	13	12	0	2	3	0	0	0	1	13	15	5	2	0	2	1	0	0	0	3	0	4	6	13		
300 hPa AGL	3	1	1	1	1	9	0	0	0	0	4	0	9	16	9	0	7	3	0	0	0	0	22	6	1	3	0	0	4	0	0	0	0	15	6	12	4		
250 hPa AGL	1	3	15	0	0	16	0	0	0	0	3	0	11	16	10	3	1	2	0	0	0	0	18	7	0	3	0	0	5	2	0	0	0	7	6	11	11		
200 hPa AGL	3	3	13	0	0	10	0	0	0	0	0	0	13	14	17	4	1	7	0	0	0	0	5	10	0	0	1	0	3	1	0	0	11	6	10	8			
150 hPa AGL	2	1	7	1	0	7	0	0	0	0	0	0	14	14	9	5	2	5	0	0	0	0	6	8	0	1	0	0	1	0	0	0	16	15	15	11			
100 hPa AGL	4	1	5	0	0	1	0	0	0	0	1	1	15	14	5	4	9	9	0	0	0	1	2	8	0	0	0	0	0	1	0	0	17	20	20	9			
50 hPa AGL	1	0	3	0	0	0	0	0	0	0	0	0	16	7	0	6	8	1	0	0	0	1	1	0	0	0	0	0	0	4	0	0	0	16	24	20	8		
40 hPa AGL	2	0	2	0	0	0	0	0	0	0	0	0	16	3	0	5	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	24	21	5			
30 hPa AGL	2	0	2	0	0	0	0	0	0	0	0	0	15	0	0	3	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	15	24	23	0			
20 hPa AGL	2	0	0	0	0	0	0	0	0	0	0	0	14	0	0	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	24	23	0			
10 hPa AGL	1	0	0	0	0	0	0	0	0	0	0	0	13	1	0	3	9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	15	24	19	0			
Period 1																			Period 2										Period 3										

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Figure 4. Number of back trajectories in each day which had specific humidity exceeding 4 g kg^{-1} at least in one 1-hour timestep during the last four days before their arrival at the location of *Oden*. Minimum number is zero trajectories meaning that there in



not even a single trajectory in which specific humidity had exceed 4 g kg^{-1} during its journey and maximum is 24 meaning that in all 24 trajectories, initialized one in every hour, specific humidity has exceeded 4 g kg^{-1} .

	8 May	9 May	10 May	11 May	12 May	13 May	14 May	15 May	16 May	17 May	18 May	19 May	20 May	21 May	22 May	23 May	24 May	25 May	26 May	27 May	28 May	29 May	30 May	31 May	1 June	2 June	3 June	4 June	5 June	6 June	7 June	8 June	9 June	10 June	11 June	12 June	13 June
300 hPa												0.01	0.02				0.26							0.00									0.02	0.01		0.01	
400 hPa		0.00	0.03		0.02	0.01		0.01	0.01		0.00	0.02	0.03	0.03	0.01	0.02	0.03	0.04	0.02	0.05		0.03	0.02	0.03	0.01			0.01				0.01		0.01	0.03	0.01	0.02
500 hPa			0.01	0.00	0.04	0.02		0.02	0.01	0.00		0.08	0.03	0.05	0.03	0.02	0.02	0.02	0.02	0.05			0.03	0.03	0.02	0.02	0.14	0.03		0.00			0.00	0.12	0.04	0.03	
600 hPa			0.01	0.03	0.03	0.06	0.02	0.01		0.01	0.01		0.03	0.05	0.02		0.03	0.06				0.03	0.02	0.02	0.01	0.02		0.09	0.03			0.03		0.04	0.03	0.03	
300 hPa AGL	0.01	0.01	0.03	0.01	0.06	0.06					0.00	0.02	0.10	0.02		0.06	0.04					0.03	0.05	0.01	0.04				0.09				0.04	0.04	0.06	0.01	
250 hPa AGL	0.02	0.12	0.06		0.07						0.04		0.04	0.02	0.04	0.02	0.01	0.01					0.04	0.06		0.13			0.04	0.03			0.05	0.04	0.09	0.05	
200 hPa AGL	0.04	0.15	0.10		0.09							0.07	0.07	0.07	0.04	0.06	0.16					0.16	0.07			0.10			0.09	0.31			0.08	0.09	0.07	0.02	
150 hPa AGL	0.05	0.03	0.03	0.03		0.02						0.07	0.13	0.20	0.12	0.09	0.13					0.04	0.14		0.34			0.16				0.11	0.07	0.06	0.08		
100 hPa AGL	0.13	0.08	0.05		0.06						0.04	0.10	0.14	0.15	0.27	0.14	0.13	0.12					0.07	0.07	0.09				0.22			0.13	0.09	0.11	0.06		
50 hPa AGL	0.07		0.06									0.26	0.20			0.20	0.26	0.13				0.03	0.03						0.07			0.16	0.22	0.15	0.21		
40 hPa AGL	0.06		0.07									0.27	0.16			0.17	0.12															0.16	0.22	0.21	0.16		
30 hPa AGL	0.08		0.28									0.32				0.22	0.22						0.32									0.13	0.27	0.25			
20 hPa AGL	0.17											0.42				0.36	0.29															0.26	0.26	0.24			
10 hPa AGL	0.18											0.39	0.28			0.45	0.48							0.40								0.38	0.29	0.25			
	Period 1																	Period 2										Period 3									

Figure 5. Relative contribution of diabatic cooling (defined as the temperature change caused by diabatic processes other than latent heating), calculated as a ratio of temperature tendency caused by the other diabatic processes to the total temperature tendency caused by both adiabatic and the other diabatic processes during moisture condensation in the moist trajectories.

Based on the trajectory analysis, specific humidity exceeded 4 g kg^{-1} more frequently during the four days leading up to the air mass arrival at *Oden* compared to the day of its arrival (compare Fig. 2a with Fig. 4). These originally moist, but later dried, air occurred especially in the mid-troposphere, above the 850 hPa. These cases co-occurred with cases of elevated specific humidity observed near the surface at *Oden*, suggesting that the moistest air masses did not reach *Oden* but had started to dry before arriving there. Drying of the air masses is mostly associated with adiabatic cooling, which is often responsible more than 90% of removal of water vapour from the air parcels that arrive at *Oden* above 850 hPa level (Fig. 5). Typical situations during the first period (8 – 25 May) were such that cyclones from the south-western side of Iceland moved towards Svalbard and Franz Josef land and the moist air mostly did not reach the Fram Strait (Fig. S4). However, occurrence of the originally moist air masses at *Oden* was associated with cases when moist air mass in a warm sector of a cyclone (Fig. S2) passed the Greenland Sea on the southern side of *Oden*. Based on the Norwegian cyclone model (Bjerknes 1919), this suggests that the originally moist air originated from the lower troposphere in the warm sector of a cyclone and were lifted on the frontal zones of the cyclone. In addition, this suggests that the warm sectors of cyclones did not extend as far north as the location of *Oden*, and that only occluded fronts passed over the research vessel. Exceptions occurred on 20 May, 24 May and 10 – 12 June, when a significant number of moist air parcels reached the location of *Oden* near the surface (Fig. 4).

3.3 Case analysis

In the following section, we will analyse the dynamic conditions and thermodynamic processes affecting the evolution of atmospheric moisture content, especially during the cases when moist air masses were observed at *Oden* or the trajectory analyses indicated that air masses higher in the troposphere had originated from the warm sector of a cyclone.

3.3.1 13 May

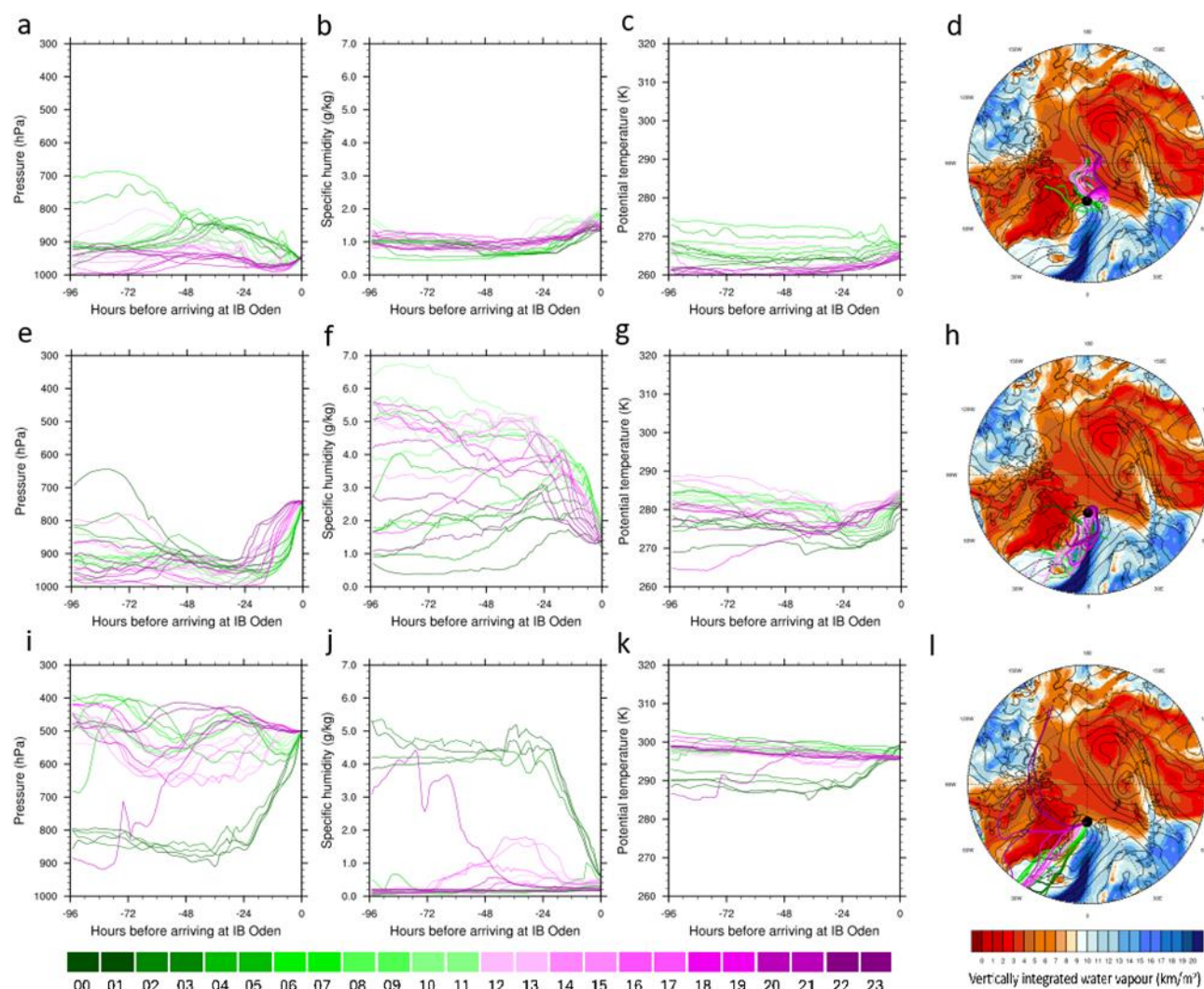


Figure 6. Pressure (left), specific humidity (middle) and potential temperature (right) along backward trajectories from initialized *Oden* at (a-c) 50 hPa AGL, (e-g) 250 hPa AGL, and (i-k) at 500 hPa between 00 – 23 UTC on 13 May (one trajectory calculated for each hour for each pressure level). The maps on the right show the horizontal tracks of trajectories during 96 hours before their arrival at *Oden* with SLP (contours) and vertically integrated water vapour (kg m⁻², colours) on 13 May 00 UTC. Green and purple colours in the lines indicate the initialization time (hour) of trajectories.

The case of 13 May represents a situation when a cyclone passed the location of *Oden* so that near surface air was all the time dry and cold northerly airmass whereas air above it had been moist and dried as a consequence of adiabatic lifting before its arrival at *Oden* (Fig. 4 and 5) which suggests the warm sector of the cyclone had occluded before it arrived at *Oden*.

On 13 May, a cyclone passed the Fram Strait on the southern side of *Oden*. However, vertically integrated water vapour (Fig. 6d) and 850 hPa level temperature (Fig. S2) indicate that the location of *Oden* was all the time north of the warm sector.



Radiosonde observations also showed that the near-surface air mass remained cold, with temperature below -10°C , and dry, specific humidity approximately 1.5 g kg^{-1} (Fig. 2). Trajectories tracks indicate that the near surface (at 50 hPa AGL), the air mass mostly originated from the central Arctic and had been originally even drier (specific humidity approx. 1.0 g kg^{-1}) but had gained moisture during the last 20 hours before arriving at *Oden* (Fig. 6b). The potential temperature of the air mass also increased (Fig. 6c) suggesting that turbulent surface fluxes heated and moistened the air during the final 20 hours before arriving at *Oden*. This was likely due to the air mass following a small loop east of *Oden* (Fig. 6d), probably over at least partially open ocean. The courses of trajectories as well as the temperature and specific humidity evolution indicate that the near surface air had not been in the warm sector of the cyclone and thus confirm that the warm sector did not reach *Oden* at the surface.

The trajectories and the evolution of temperature and specific humidity along them differed between the levels 50 hPa AGL and 250 hPa AGL. At the higher level most trajectories originated far south of *Oden* (Fig. 6h). These trajectories further indicate that the air mass arriving at *Oden* at 250 hPa AGL had earlier been remarkably moister, with specific humidity decreasing approximately 4 g kg^{-1} during the last 20 hours before arrival (Fig. 6f). This was caused by adiabatic cooling due to lifting of air mass by approximately 200 hPa (Fig. 6e). Simultaneously, potential temperature increased 10 K, from 270 – 275 K to 280 – 285 K, due to condensation (Fig. 6g). The trajectory analysis also indicates that mid-tropospheric air, which had its origin near the surface in the warm sector of the cyclone, arrived at *Oden* already earlier, during the second half of 12 May (Fig. S6) and first four hours of 13 May (Fig. 6i). Later the air arriving at *Oden* had been in the middle of the troposphere all the time (Fig. 6i). These mid-tropospheric air parcels, which had been lifted from the lower troposphere, were warmer and often also moister than the air parcels arriving at *Oden* at lower altitudes (Fig. 6j and 6k). Because they were warmer and moister, they ascended to higher potential temperature levels, corresponding to higher altitudes in the atmosphere. Moisture was primarily removed from these air masses through cooling associated with adiabatic lifting, as their temperature evolution closely followed pseudoadiabatic lapse rates (Fig. S7).

The situation on 10th May resembled that on 13th May, except that near-surface air mass had travelled a longer loop over the open ocean in the Barents Sea and was therefore moister. The 13 May case was examined here because it exhibits a stronger contrast between a cold and dry near-surface air originating from the central Arctic and warm and moist air of southerly origin aloft.

3.3.2 20 May

On the contrast to the case 13 May, on 20 May also near surface airmass was moist (Fig. 2 and 4) suggesting that a warm sector reached the location of *Oden* at surface. The situation on 20 May was dynamically rather similar to that on 13 May, except that the route of the cyclone that passed the Fram Strait was more northerly. The cyclone track allowed the warm sector to reach *Oden* at the surface. This is indicated by high near-surface specific humidity ($> 4 \text{ g kg}^{-1}$) and temperatures close to 0°C (Fig. 2). Trajectory analysis further supports the presence of a warm southerly air mass at the surface at *Oden*. During 20 May, the near-surface air mass (50 hPa AGL) originated over the northern North Atlantic, located over the Iceland Sea two



days prior to arrival at *Oden* (Fig. 7d). Many trajectories indicate that this air mass remained very close to the surface (Fig. 7a) with specific humidity exceeding 5 g kg^{-1} before being lifted by approximately 50 hPa during the 20 hours preceding arrival (Fig. 7b). Prior to the arrival of this moist air mass, during the first half of the day (green lines in Fig. 7), air parcels descended from Greenland. These parcels were originally dry but gained moisture during the 24 hours before arrival. This air mass probably represented a prefrontal air mass that was not part of the warm sector.

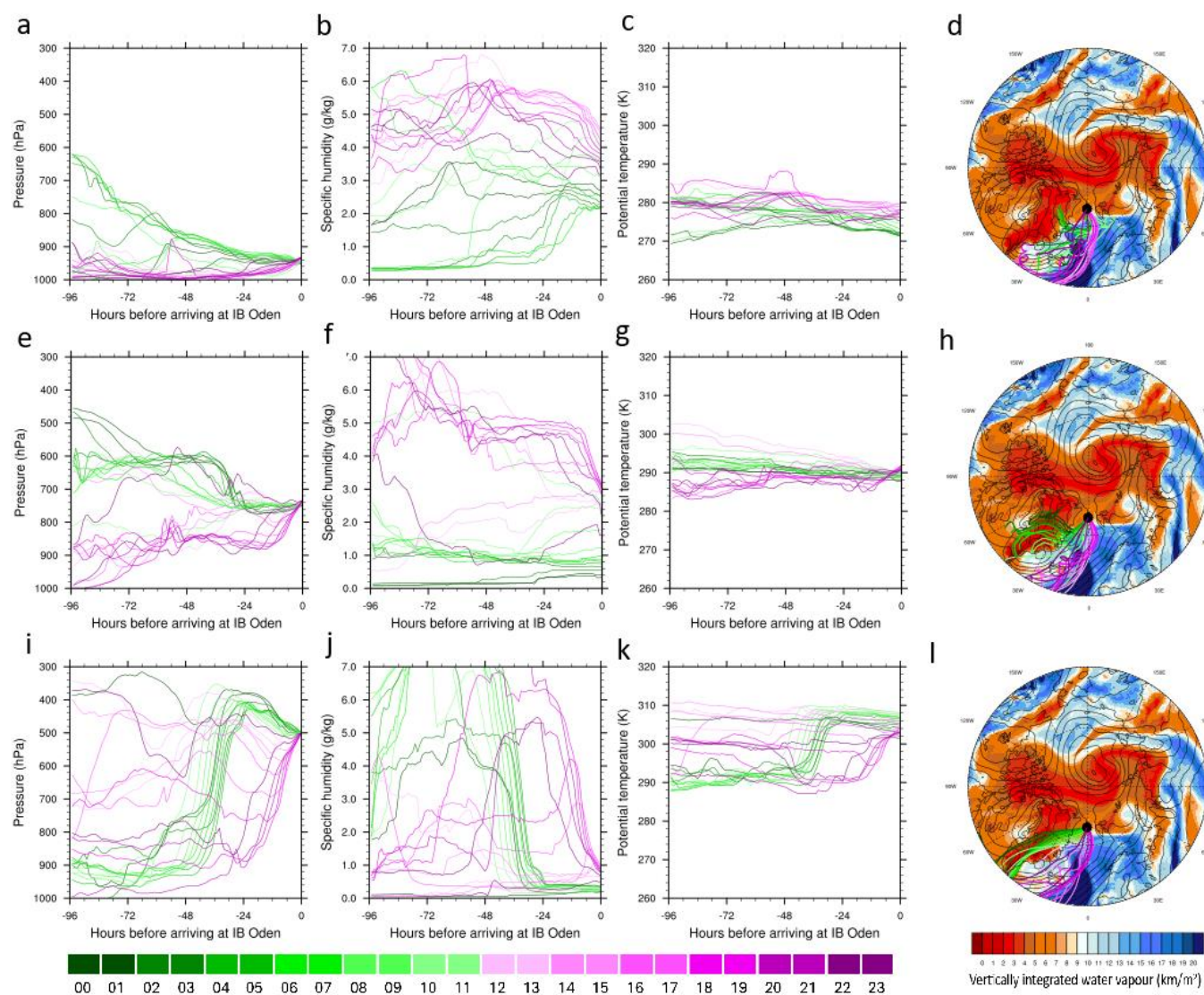


Figure 7. As in Fig. 6 but for 20 May.

The specific humidity of air parcels arriving at *Oden* at 250 hPa AGL that had not crossed Greenland was initially almost similar to that of parcels arriving at lower levels, even though these air masses had not been in contact with the surface, indicating long range moisture transport (magenta lines in Fig. 7f). As these air masses were lifted from approximately 900 to

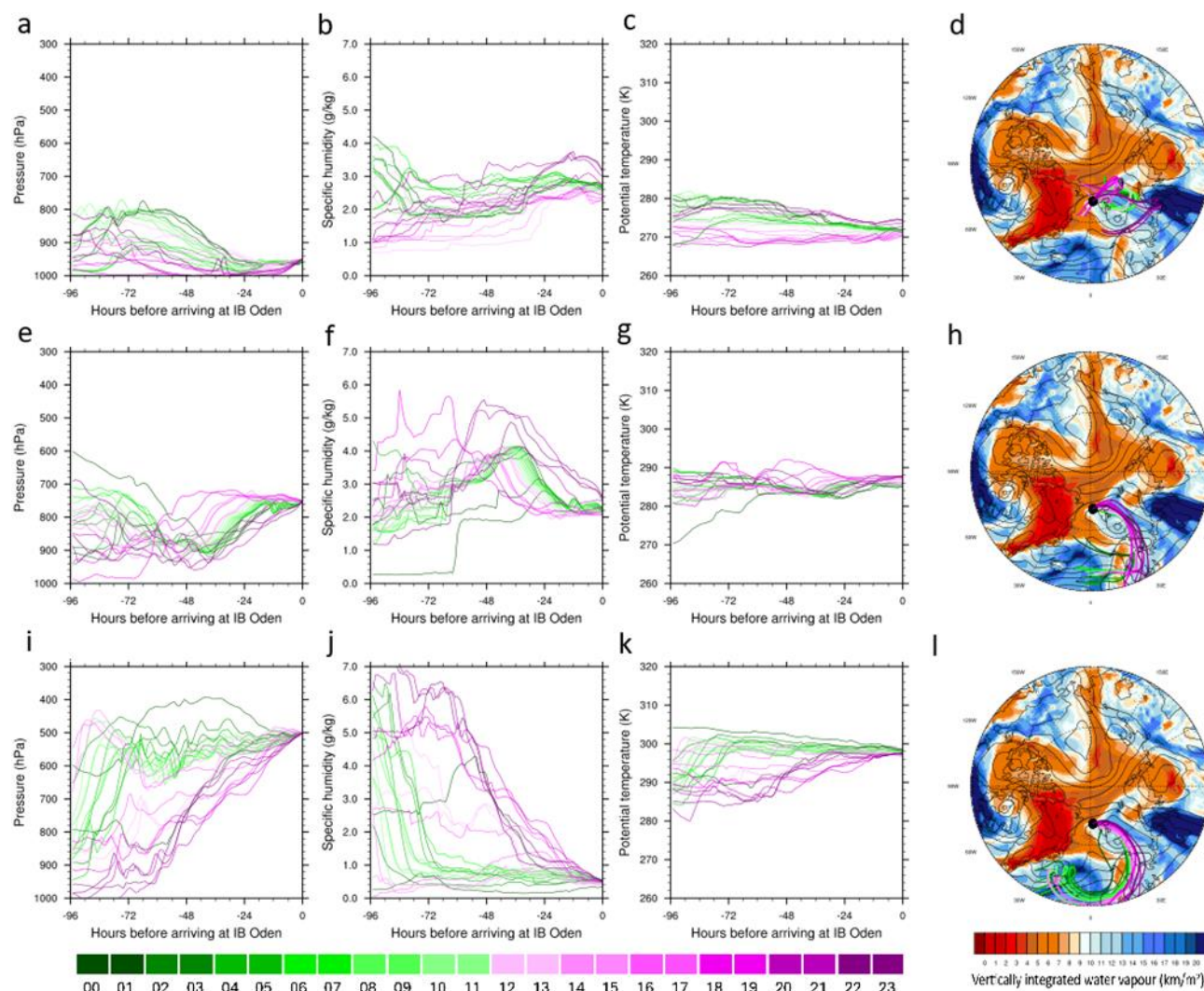


750 hPa, they became progressively drier, while condensation led to a slight increase in potential temperature (Fig. 7g). The
345 most pronounced changes occurred during the last day before the arrival at *Oden*. However, in contrast to 13 May, on 20 May
many air parcels arriving at *Oden* at 250 hPa AGL or higher had crossed Greenland and were originally dry or, especially air
parcels arrived at 500 hPa level, had dried due to orographic lifting during the crossing of Greenland (green lines in Fig. 7f,
h, j and l).

Following the case of 20 May, a rather similar moisture transport event occurred on 23 to 25 May, when the warm sector again
350 reached the location of *Oden*. Although the near-surface air mass was in both cases transported northward from the south to
Oden, the moistest air was advected across the Norwegian Sea towards Scandinavia and the Barents Sea, remaining far
southeast of the Fram Strait (Fig. S4).

3.3.3 30 – 31 May

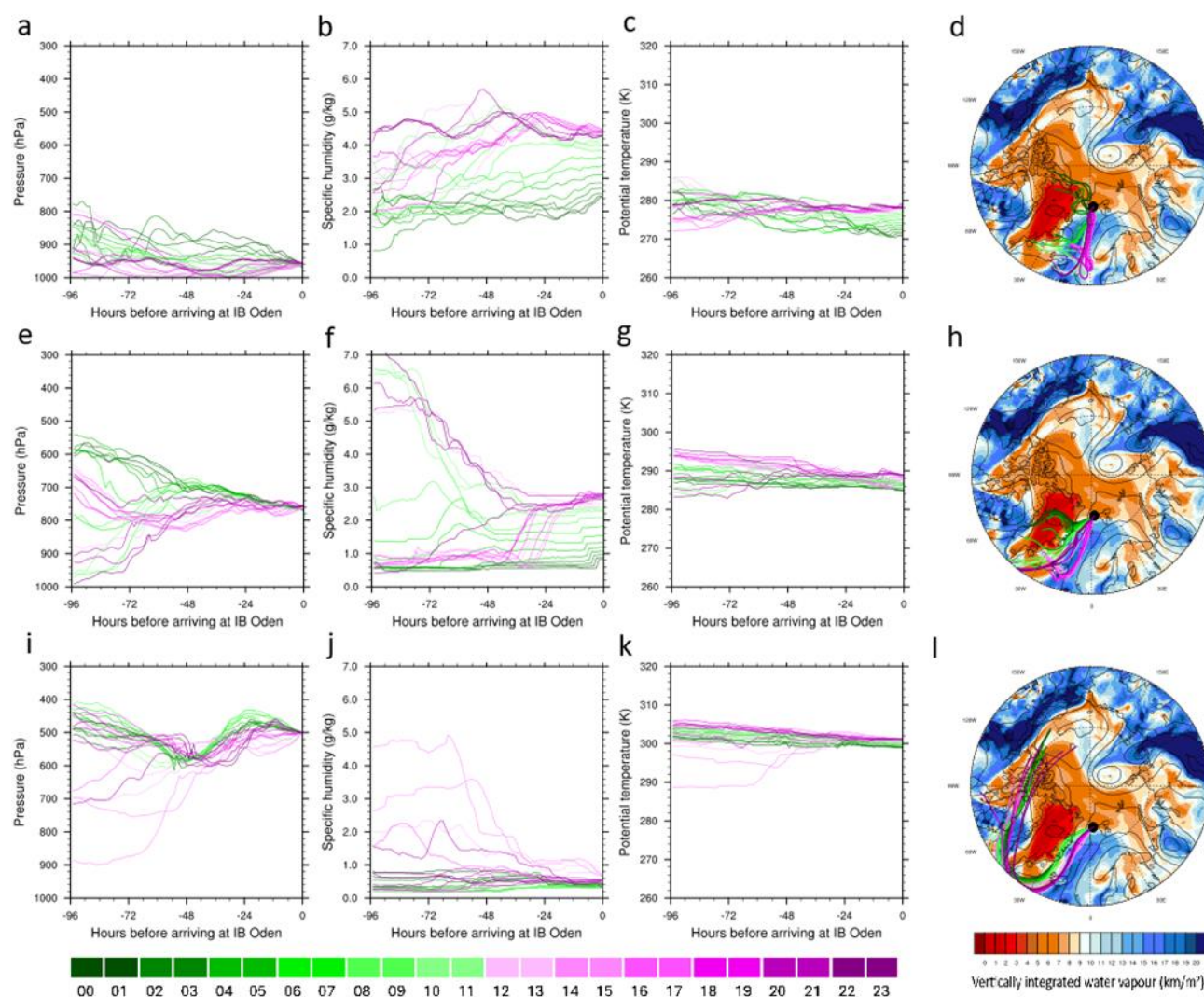
On 30 - 31 May, south-easterly airflow across the Barents Sea towards Svalbard and the Fram Strait caused by a cyclone on
355 the eastern side of the upper tropospheric trough (Fig. S1, S2 and S3), transported moisture from northeastern Europe towards
the Fram Strait (Fig. 8). Radiosonde observations showed that near-surface temperature increased by approximately 5°C and
specific humidity by about 3 g kg⁻¹ at *Oden* (Fig. 2). However, in the middle troposphere the air had been notably moister prior
to arriving at *Oden* (Fig. 8f). Trajectory analysis indicates that the near-surface (50 hPa AGL) air had been over the Arctic
Ocean and the Barents Sea and was therefore not much moister before arriving at *Oden*, instead many air parcels gained
360 moisture during the last 60 hours before reaching *Oden*. Air reaching *Oden* at 250 hPa AGL and at 500 hPa had originated
from farther south and travelled across northern continental Europe (Fig. 8h and l). These air masses were mostly lifted and
dried more than 20 hours before arrival at *Oden*, with only minor changes in altitude and specific humidity during the last 20
hours (Fig. 8e - f and 8i - j).



365 **Figure 8.** As in Figure 6 but for 30 May.

3.3.4 10 - 11 June

The final event of transport of warm, moist air to the Fram Strait during the ARTofMELT expedition occurred on 10-12 June, when a moist air mass flowed from the northern North Atlantic to the Fram Strait along the western flank of a surface anticyclone (Fig. 1f and S2). Radiosonde observation showed that during this event the near-surface specific humidity was approximately 4.5 g kg^{-1} and temperature exceeded 0°C , representing the warmest and moistest near-surface air mass observed during the entire expedition (Fig. 2). The near-surface air mass originated from the northern North Atlantic, between Greenland and Scandinavia (Fig. 9d), and did not lose moisture prior to the arrival at *Oden*. In fact, many trajectories indicate an increase in specific humidity meanwhile the air mass travelled over the Norwegian Sea (Fig. 9b).



375 **Figure 9.** As in Figure 6 but for 10 June.

Even among the trajectories arriving at *Oden* higher in the troposphere, only a few indicate long-range transports of very moist near-surface air masses from far south. Instead, most trajectories indicate that the mid-tropospheric air mass did not exhibit much vertical displacement and remained dry during the four days preceding arrival at *Oden* and thus did not contribute remarkably to northward moisture transport (Fig. 9i and j).

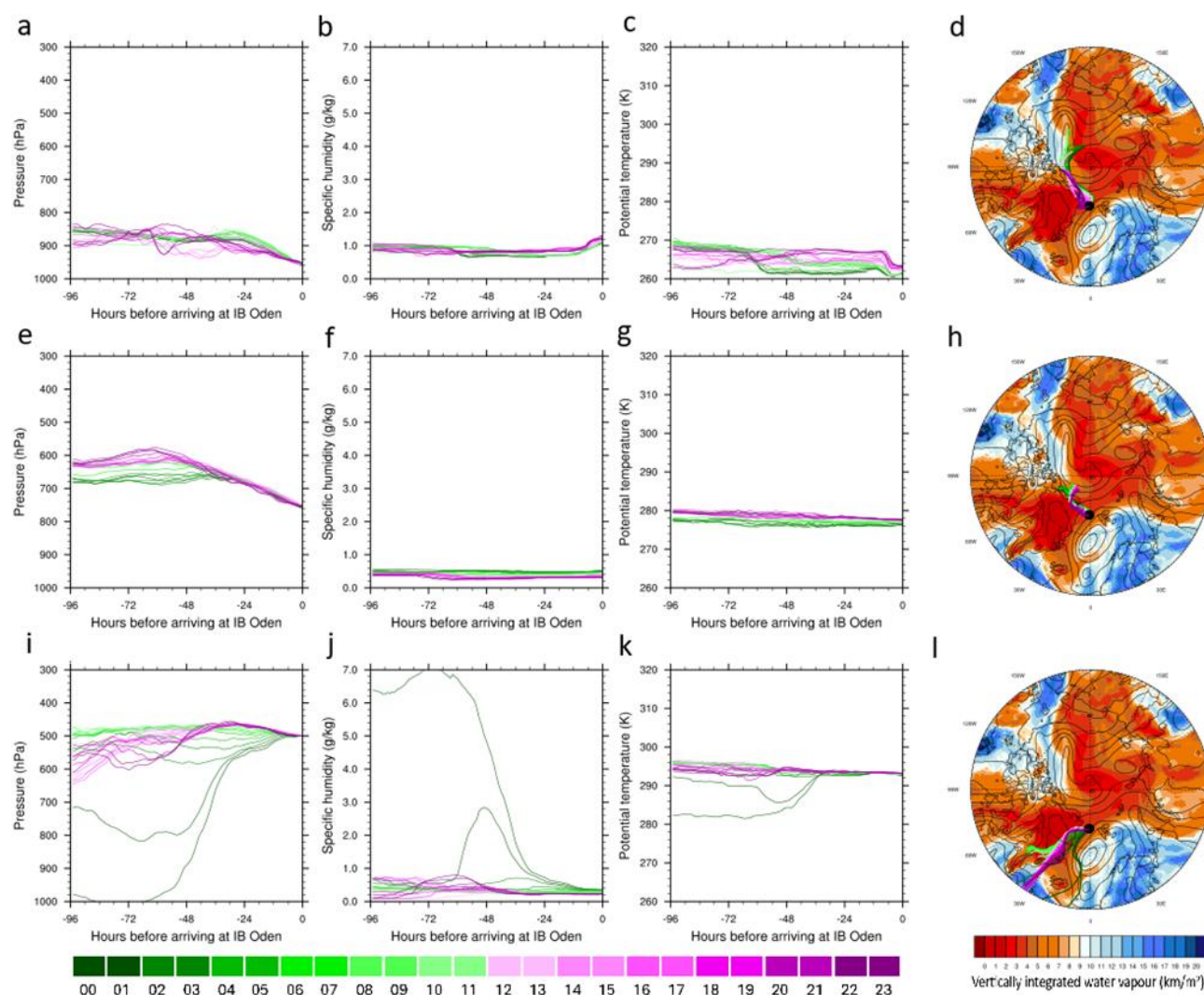
380 3.3.5 Dry days (e.g., 16 May)

Between the days when moist or originally moist air masses were transported to *Oden*, there were several days characterized by very dry conditions. During these periods, few or no trajectories indicated elevated specific humidity at any time within the



four days preceding arrival at *Oden* (Fig. 4). Many such dry days during the ARTofMELT expedition were associated with northerly flow and low specific humidity.

385 The driest air mass during the entire expedition, based on conditions during the four days preceding arrival at *Oden*, was observed on 16 May. The trajectories indicate that the air mass was dry throughout the troposphere, with specific humidity exceeding 1 g kg^{-1} only near the surface and only in a few trajectories in the upper troposphere during this period (Fig. 10b, f, j). Such dry days were typically associated with northerly advection of cold air mass following a cyclone passage, as on 16 May (Fig. 10d and h). Trajectories arriving at *Oden* in the lower troposphere (50 hPa AGL and 250 hPa AGL) indicate weak
390 winds (Fig. 10d and h) and subsidence (Fig. 10a and e) associated with a low-level ridge. Trajectories arriving 50 hPa AGL indicate moistening during the final 12 hours before arrival (Fig. 10b), accompanied by a decrease in potential temperature (Fig. 10c). This was probably associated with evaporation of precipitation, as the trajectories did not reach the surface and the decrease in the potential temperature indicates a conversion of dry static energy to latent heat.



395 **Figure 10.** As in Figure 6 but for 16 May.

4. Discussion

Atmospheric moisture conditions in the Arctic are mostly determined by the following processes: the transport of warm, moist air masses from mid-latitudes, and the drying of air masses in the Arctic due to adiabatic cooling driven by dynamic processes or diabatic cooling driven by thermodynamic processes. These processes are strongly constrained by atmospheric large- and synoptic-scale dynamics. In this study, we examined the dynamic and thermodynamic factors, which generated anomalously dry conditions in the Fram Strait during the ARTofMELT expedition in May and June 2023.

During approximately the first half of the expedition (8 – 25 May) large-scale circulation patterns were characterized by southwest – northeast directed jet stream associated with baroclinic conditions in the northern North Atlantic. This pattern



favours relatively fast north-eastward movement of cyclones, which enhanced north-eastward moisture transport over the
405 Nordic Seas. The northward moisture transport associated with synoptic-scale cyclones occurs especially in the warm sector
of cyclones. During evolution of an extratropical cyclone, the warm sector first becomes narrower, as the warm air mass is
lifted in the frontal zone, and finally the whole warm sector occludes so that the warm air mass is no more in contact with the
sea surface. Our results indicate that this process was responsible for most of the condensation of northward moving water
vapour, and thus for drying of the air mass. These factors caused a sharp contrast in moisture conditions between the Fram
410 Strait and the Norwegian and Barents Seas. Over the Norwegian and Barents Seas, the air mass was anomalously warm and
moist; however, due to the cyclone tracks, the Fram Strait remained predominantly on the cold side of the cyclones during the
study period. Most importantly, the late onset of surface melt was likely caused by the persistent northerly flow over much of
the Nordic Seas during the latter half of the expedition. Advection of dry air mass from the north, presented in the 5th case
study, resulted in formation of a large dry anomaly that expanded from the Fram Strait to Scandinavia. The processes affecting
415 the drying of those dry northerly air masses were not analysed in this study as the evolution of air mass properties was only
examined during last four days prior to arrival at *Oden*. In this study, these air masses were considered originally dry; they had
likely dried at some earlier stage due to adiabatic cooling followed by subsidence or due to air mass transformation.

The large-scale circulation patterns substantially changed during the last days of the expedition, finally leading to advection
of warm and moist air mass to the Fram Strait. In fact, the large-scale circulation pattern during the last days of the expedition,
420 shown in the 4th case study, resembled that in the first period but meridional winds were stronger during the last days. This
co-occurred with a high pressure blocking over Scandinavia. Many studies (Woods et al., 2013; You et al., 2022b; Faeron et
al., 2021) have shown that blockings that steer the cyclone tracks towards north are often a prerequisite for strong moisture
transport to the Arctic. These events are often associated with a barotropic temperature structure allowing near-surface
transport of air mass to the Arctic without lifting and drying of the air mass in frontal zones (Ali and Pithan 2020; Papritz et
425 al., 2023; Svensson et al., 2023; Karalis et al., 2025).

Baroclinicity affects moisture transport into the Arctic. Our results indicate that baroclinicity in the Nordic Seas weakens
moisture transport in the high Arctic but may increase moisture transport towards the Barents and Kara seas. In baroclinic
conditions, moisture transport to the inner Arctic is prevented by the fast development of cyclones, occlusion of the warm
sector, and the strong zonally orientated jets stream. In such conditions, a large part of the moisture is removed from the air
430 due to adiabatic lifting and condensation in the barocline zone, i.e., the frontal zone between cold and warm air masses. This
result is in line with the conclusion of Papritz et al., (2022), who pointed out that strong baroclinicity leads upward motions of
air mass along isentropes, resulting in moisture condensation due to adiabatic cooling.

In the light of our results from the 1st and 3rd periods, we also speculate that, for an equivalent amount of moisture transported
into the Arctic, the resulting warming effect is greater under barotropic than under baroclinic conditions. This is because a
435 large part of the near-surface warming effect of moisture transport originates from the effects of cloudiness on longwave
radiation (Hao et al., 2021). A certain amount of moisture transported towards the Arctic under barotropic conditions, when
moisture is slowly removed from the air mass due to longwave radiative cooling, may have a larger warming effect at the



surface than the same amount of moisture transported under baroclinic conditions, when uplift and adiabatic cooling lead to relatively fast removal of moisture. This suggests that dynamical conditions affecting moisture transport and the co-work
 440 between SLP dipoles / blocks to the east in steering the moisture into the Arctic are not only important for the strength of moisture transport, but they also substantially affect the total effect of moisture transport on the Arctic warming.

5. Conclusion

Strong events of moisture transport, associated with enhanced downward longwave radiation due to increased cloudiness, often cause the onset of surface melt in high Arctic in late spring or early summer. To improve knowledge on processes leading to
 445 the onset of surface melt, the ARTofMELT expedition was carried out in May - June 2023. In that spring, the onset of surface melt occurred exceptionally late, which in this study is examined from the point of view of atmospheric moisture and its transport to the Arctic. In this context, the delayed onset of surface melt on the Fram Strait in spring 2023 was driven by dry conditions associated with storm tracks located south of the Fram Strait in early and mid-May as well as by persistent northerly flow in late May and early June. Although air masses over the northern North-Atlantic and Barents Sea were anomalously
 450 warm and moist in early and mid-May, they did not reach the Fram Strait or the location of *Oden*. This contrast between relatively high air temperatures and low atmospheric moisture was primarily controlled by the routes of cyclones during this period. Cyclone tracks were directed from the southeastern coast of Greenland towards Svalbard and the northern Barents Sea, remaining south of the Fram Strait. As a result, moist air mass within the warm sectors of these cyclones rarely reached the location of *Oden* at the surface, except briefly on 20 May.

455 The above demonstrates that cyclones tracks are critical to the northward extent of moisture transport and may cause large contrasts in moisture conditions over relatively short distances. However, even though moist air at the surface did not reach the Fram Strait, the trajectory analysis showed that in some cases the air mass in the upper troposphere had been moist prior to arrival at the location of *Oden*. These air masses originated from the warm sector of cyclones. Lifting of air masses over colder, northward-origin air mass in frontal zones led to adiabatic cooling and subsequent moisture condensation. This
 460 condensation associated with adiabatic lifting accounted for the majority of drying in the air that reached the location of *Oden*. In originally moist air masses, adiabatic lifting was responsible for more than 90% of the drying above 200 hPa AGL. These results suggest that air mass transformation played a relatively minor role in air mass drying during the expedition. However, the location of *Oden* near the sea ice margin likely limited substantial modification of air mass properties through diabatic cooling processes, as the air mass had not spent sufficient time over sea ice prior to reaching the site. Furthermore, the
 465 prevailing circulation patterns generally inhibited near-surface moisture transport farther into the Arctic.

During the last days of the expedition in mid-June, the large-scale circulation became more favourable for moisture advection over the Fram Strait. This was associated with a more meridional flow pattern, characterized by a stronger northward wind component and a less baroclinic temperature field in south–north direction. These conditions facilitated the advection of moist



air into the Fram Strait at the surface, and lead to the onset of surface melt. This suggests that reduced baroclinicity enhances
470 the penetration of moist air masses farther into the Arctic.

Overall, these results highlight the important role of adiabatic lifting in frontal zones of cyclones in drying northward
transported moist air masses, while also leaving open the question of the potential role of diabatic processes (i.e., air mass
transformation) in air mass drying. This role may become more significant, if the reference location of the analysis were situated
farther north of the ice edge or if circulation patterns favoured the advection of moist air masses into the high Arctic.

475 **Code and data availability**

LAGRANTO code is available from <https://iacweb.ethz.ch/staff/sprenger/lagranto/index.html>

MOAAP code is available from <https://github.com/AndreasPrein/MOAAP>

Other analysing and plotting codes, including Bash, CDO (Climate Data Operators), NCL (NCAR Command Language), and
Python scripts, are available from authors upon request.

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All data from the ARTofMELT expedition are available on the Boline Centre for Climate Research database at:
<https://doi.org/10.17043/oden-artofmelt-2023-expedition>.

The ERA5 reanalysis is found at <https://cds.climate.copernicus.eu/datasets/>

Supplement link

485 The link to the supplement will be included by Copernicus, if applicable.

Author contributions

TN and TV designed the study

TN and SM carried out the analysis

All authors contribute to writing the manuscript

490 **Competing interests**

Authors has not competing interest.



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References

- 510 Ali, S.M. and Pithan, F.: Following moist intrusions into the Arctic using SHEBA observations in a Lagrangian perspective,
 Quarterly Journal of the Royal Meteorological Society, 146(732), 3522-3533, <https://doi.org/10.1002/qj.3859>, 2020.
- Batrak, Y. and Müller, M.: On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice.
 Nature Communications, 10(1), 4170, <https://doi.org/10.1038/s41467-019-11975-3>, 2019.
- Bjerknes, J.: On the structure of moving cyclones. Monthly Weather Review, 47(2), 95-99. [https://doi.org/10.1175/1520-0493\(1919\)47<95:OTSOMC>2.0.CO;2](https://doi.org/10.1175/1520-0493(1919)47<95:OTSOMC>2.0.CO;2), 1919
 515
- Fearon, M.G., Doyle, J.D., Ryglicki, D.R., Finocchio, P.M. and Sprenger, M.: The role of cyclones in moisture transport into
 the Arctic. Geophysical Research Letters, 48(4), p.e2020GL090353, <https://doi.org/10.1029/2020GL090353>, 2021
- Graham, R.M., Hudson, S.R. and Maturilli, M.: Improved performance of ERA5 in Arctic gateway relative to four global
 atmospheric reanalyses. Geophysical Research Letters, 46(11), 6138-6147, <https://doi.org/10.1029/2019GL082781>, 2019



- 520 Groves, D. G., and Francis, J. A. Moisture budget of the Arctic atmosphere from TOVS satellite data, *J. Geophys. Res.*, 107(D19), 4391, <https://doi.org/10.1029/2001JD001191>, 2002
- Hao M, Lin Y, Luo Y, Nath R, Zhao Z. The impact of atmospheric moisture transport on winter Arctic warming: Radiation versus latent heat release. *International Journal Climatology*, 41(7), 3982–3993. <https://doi.org/10.1002/joc.7054>, 2021
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. ... and Simmons, A.: The ERA5 global reanalysis. *Quarterly journal of the royal meteorological society*, 146(730), 1999-2049, <https://doi.org/10.1002/qj.3803>, 2020
- 525 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., and Thépaut, J.-N.: ERA5 hourly data on single levels from 1940 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS) [data set], <https://doi.org/10.24381/cds.adbb2d47>, 2023a
- 530 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., and Thépaut, J.-N.: ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS) [data set], <https://doi.org/10.24381/cds.bd0915c6>, 2023b
- Jensen, M.P., Holdridge, D.J., Survo, P., Lehtinen, R., Baxter, S., Toto, T. and Johnson, K.L.: Comparison of Vaisala radiosondes RS41 and RS92 at the ARM Southern Great Plains site. *Atmospheric Measurement Techniques*, 9(7), 3115–3129. <https://doi.org/10.5194/amt-9-3115-2016>, 2016
- 535 Kapsch, M.L., Graversen, R.G. and Tjernström, M., 2013. Springtime atmospheric energy transport and the control of Arctic summer sea-ice extent. *Nature Climate Change*, 3(8), 744–748, <https://doi.org/10.1038/nclimate1884>, 2013
- Kapsch, M.L., Skific, N., Graversen, R.G., Tjernström, M. and Francis, J.A.: Summers with low Arctic sea ice linked to persistence of spring atmospheric circulation patterns. *Climate dynamics*, 52(3), 2497–2512, [https://doi.org/10.1007/s00382-](https://doi.org/10.1007/s00382-018-4279-z)
- 540 018-4279-z, 2019
- Karalis, M., Svensson, G., Wendisch, M. and Tjernström, M.: Lagrangian single-column modeling of Arctic air mass transformation during HALO-(A C)3, *Atmospheric Chemistry and Physics*, 25(20), 13177–13198, <https://doi.org/10.5194/acp-25-13177-2025>, 2025
- Laxon, S. W., Peacock, N. and Smith, D.: High interannual variability of sea ice thickness in the Arctic region, *Nature*, 425, 947–950, <https://doi.org/10.1038/nature02050>, 2003.
- 545 Liu, Y., Kay, J. R., Vavrus, S., and Woods, C.: Time evolution of the cloud response to moisture intrusions into the Arctic during winter. *Journal of Climate*, 31, 9389–9405, <https://doi.org/10.1175/JCLI-D-17-0896.1>, 2018
- Luo, B., Luo, D., Wu, L., Zhong, L. and Simmonds, I.: Atmospheric circulation patterns which promote winter Arctic sea ice decline. *Environmental Research Letters*, 12(5), p.054017, <https://doi.org/10.1088/1748-9326/aa69d0>, 2017
- 550 Maksimovich, E., and Vihma, T.: The effect of surface heat fluxes on interannual variability in the spring onset of snow melt in the central Arctic Ocean, *Journal of*, 117, C07012, <https://doi.org/10.1029/2011JC007220>. 2012



- Mortin, J., Svensson, G., Graversen, R. G., Kapsch, M.-L., Stroeve, J. C., and Boisvert L. N.: Melt onset over Arctic sea ice controlled by atmospheric moisture transport, *Geophysical Research Letters*, 43(12), 6636–6642, <https://doi.org/10.1002/2016GL069330>, 2016
- 555 Murto, S., Caballero, R., Svensson, G. and Papritz, L.: Interaction between Atlantic cyclones and Eurasian atmospheric blocking drives wintertime warm extremes in the high Arctic. *Weather and Climate Dynamics*, 3(1), 21–44, <https://doi.org/10.5194/wcd-3-21-2022>, 2022
- Murto, S., Papritz, L., Messori, G., Caballero, R., Svensson, G. and Wernli, H., 2023. Extreme surface energy budget anomalies in the high Arctic in winter. *Journal of Climate*, 36(11), 3591–3609, <https://doi.org/10.1175/JCLI-D-22-0209.1>, 2023
- 560 Murto, S., Tjernström, M., Brooks, I., Guy, H., Karalis, M., Vihma, T., Urbancic, G., Prytherch, J.: Radiosonde profiles from expedition ARTofMELT, Arctic Ocean 2023. Dataset version 1. [dataset]. Bolin Centre Database. <https://doi.org/10.17043/oden-artofmelt-2023-radiosonde-1>, 2024a
- Murto, S., and Tjernström, M.: Backward trajectories along the ship track using the LAGRANTO model, for the expedition ARTofMELT, Arctic Ocean 2023. Dataset version 1. [dataset]. Bolin Centre Database. [https://doi.org/10.17043/oden-](https://doi.org/10.17043/oden-artofmelt-2023-trajectories-backward-ship-1)
- 565 [artofmelt-2023-trajectories-backward-ship-1](https://doi.org/10.17043/oden-artofmelt-2023-trajectories-backward-ship-1), 2024b
- Murto, S., Svensson, G. and Caballero, R., Characteristics of springtime surface energy budget anomalies and their relation to Arctic melt onset dates. *Journal of Climate*, 39(11), 2907–2924, <https://doi.org/10.1175/JCLI-D-25-0382.1>, 2026.
- Naakka, T., Nygård, T., Vihma, T., Sedlar, J. and Graversen, R.: Atmospheric moisture transport between mid-latitudes and the Arctic: Regional, seasonal and vertical distributions. *International Journal of Climatology*, 39(6), 2862–2879, <https://doi.org/10.1002/joc.5988>, 2019
- 570 Nash, D., Waliser, D., Guan, B., Ye, H. and Ralph, F. M.: The role of atmospheric rivers in extratropical and polar hydroclimate. *Journal of Geophysical Research: Atmospheres* 123(13), 6804–6821, <https://doi.org/10.1029/2017JD028130>, 2018
- Neiman, P. J., Ralph, F. M., Wick, G. A., Lundquist, J. D. and Dettinger, M. D.: 2008. Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. *Journal of Hydrometeorology*, 9(1), 22–47. <https://doi.org/10.1175/2007JHM855.1>, 2008
- 575 Newman, M., Kiladis, G. N., Weickmann, K. M., Ralph, F. M. and Sardeshmukh, P. D.: Relative contributions of synoptic and low-frequency eddies to time-mean atmospheric moisture transport, including the role of atmospheric rivers. *Journal of Climate*, 25(21), 7341–7361. <https://doi.org/10.1175/JCLI-D-11-00665.1>, 2012
- 580 Papritz, L., Hauswirth, D., and Hartmuth, K.: Moisture origin, transport pathways, and driving processes of intense wintertime moisture transport into the Arctic, *Weather Climate Dynamics*, 3(1), 1–20, <https://doi.org/10.5194/wcd-3-1-2022>, 2022.
- Papritz, L., Murto, S., Röthlisberger, M., Caballero, R., Messori, G., Svensson, G. and Wernli, H.: The role of local and remote processes for wintertime surface energy budget extremes over Arctic sea ice. *Journal of Climate*, 36(21), 7657–7674. <https://doi.org/10.1175/JCLI-D-22-0883.1>, 2023



- 585 Pithan, F., Svensson, G., Caballero, R., Chechin, D., Cronin, T. W., Ekman, A. M., Neggers, R., Shupe, M. D., Solomon, A.,
 Tjernström, M., and Wendisch, M.: 2018. Role of air-mass transformations in exchange between the Arctic and mid-latitudes.
 Nature Geoscience 11(11): 805–812. <https://doi.org/10.1038/s41561-018-0234-1>, 2018
- Prein, A. F., Mooney, P. A. and Done, J. M.: The multi-scale interactions of atmospheric phenomenon in mean and extreme
 precipitation. Earth's Future, 11(11), p.e2023EF003534. <https://doi.org/10.1029/2023EF003534>, 2023
- 590 Sinclair, V. A., and Dacre, H. F.: Which extratropical cyclones contribute most to the transport of moisture in the Southern
 Hemisphere? Journal of Geophysical Research: Atmospheres, 124(5), 2525–2545. <https://doi.org/10.1029/2018JD028766>
 2019
- Singh, J., Diao, M., Desai, N., Shi, Y., and Liu, X.: Investigation of Arctic cloud properties and surface radiation based on
 MOSAiC shipborne observations. Journal of Geophysical Research: Atmospheres, 130(22), e2025JD044239.
 595 <https://doi.org/10.1029/2025JD044239>, 2025
- Sprenger, M. and Wernli, H.: The LAGRANTO Lagrangian analysis tool – version 2.0, Geoscientific Model Development,
 8(8), 2569–2586, <https://doi.org/10.5194/gmd-8-2569-2015>, 2015
- Stroeve, J. C., Markus, T., Boisvert, L., Miller, J., and Barrett A.: Changes in Arctic melt season and implications for sea ice
 loss, Geophysical Research Letters, 41(4), 1216–1225, <https://doi.org/10.1002/2013GL058951>. 2014
- 600 Svensson, G., Murto, S., Shupe, M. D., Pithan, F., Magnusson, L., Day, J. J., Doyle, J. D., Renfrew, I. A., Spengler, T., and
 Vihma T.: Warm air intrusions reaching the MOSAiC expedition in 2 April 2020 – the YOPP targeted observing period (TOP).
 Elementa: Science of the Anthropocene, 11(1), <https://doi.org/10.1525/elementa.2023.00016>, 2023
- Tjernström, M., Svensson, G., Magnusson, L., Brooks, I.M., Prytherch, J., Vüllers, J. and Young, G.: Central Arctic weather
 forecasting: Confronting the ECMWF IFS with observations from the Arctic Ocean 2018 expedition. Quarterly Journal of the
 605 Royal Meteorological Society, 147(735), 1278–1299, <https://doi.org/10.1002/qj.3971>, 2021
- Tjernström, M., and Zieger, P., et al.: ARTofMELT 2023 - Expedition report. Swedish Polar Research Secretariat, 124 pp.,
 ISBN 978-91-519-5134-8, Available at <https://www.polar.se/en/expeditions/expedition-reports>, 2025.
- Vihma, T., Screen, J., Tjernström, M., Newton, B., Zhang, X., Popova, V., Deser, C., Holland, M., and Prowse T.: The
 atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts, Journal of
 610 Geophysical Research Biogeosciences, 121(3), 586–620, <https://doi.org/10.1002/2015JG003132>, 2016
- Wang, C., Graham, R. M., Wang, K., Gerland, S. and Granskog, M. A.: Comparison of ERA5 and ERA-Interim near-surface
 air temperature, snowfall and precipitation over Arctic sea ice: effects on sea ice thermodynamics and evolution. The
 Cryosphere, 13(6), 1661–1679. <https://doi.org/10.5194/tc-13-1661-2019>, 2019
- Wang, C., Granskog, M. A., Hudson, S. R., Gerland, S., Pavlov, A. K., Perovich, D. K. and Nicolaus, M.: Atmospheric
 615 conditions in the central Arctic Ocean through the melt seasons of 2012 and 2013: Impact on surface conditions and solar
 energy deposition into the ice-ocean system. Journal of Geophysical Research: Atmospheres, 121(3), 1043–1058,
<https://doi.org/10.1002/2015JD023712>, 2016



- Wendisch, M., Kirbus, B., Ori, D., Shupe, M.D., Crewell, S., Sodemann, H. and Schemann, V.: Observed and modeled Arctic airmass transformations during warm air intrusions and cold air outbreaks. *Atmospheric Chemistry and Physics*, 25(21), 15047-15076. <https://doi.org/10.5194/acp-25-15047-2025>, 2025
- Woods, C., Caballero, R. and Svensson, G.: Large-scale circulation associated with moisture intrusions into the Arctic during winter. *Geophysical Research Letters*, 40(17), 4717-4721, <https://doi.org/10.1002/grl.50912>, 2013
- You, C., Tjernström, M. and Devasthale, A.: Warm and moist air intrusions into the winter Arctic: a Lagrangian view on the near-surface energy budgets. *Atmospheric Chemistry and Physics*, 22(12), 8037-8057, [https://doi.org/10.5194/acp-22-8037-](https://doi.org/10.5194/acp-22-8037-2022) 2022, 2022a
- You, C., Tjernström, M., Devasthale, A. and Steinfeld, D.: The role of atmospheric blocking in regulating arctic warming. *Geophysical Research Letters*, 49(12), p.e2022GL097899. <https://doi.org/10.1029/2022GL097899>, 2022b
- Zhang, C., Cassano, J.J., Seefeldt, M.W., Wang, H., Ma, W. and Tung, W.W.: Quantifying the impacts of atmospheric rivers on the surface energy budget of the Arctic based on reanalysis. *The Cryosphere*, 19(10), pp.4671-4699. <https://doi.org/10.5194/tc-19-4671-2025>, 2025